Off-axis Neutrinos

Gina Rameika

Fermilab

May 20, 2006

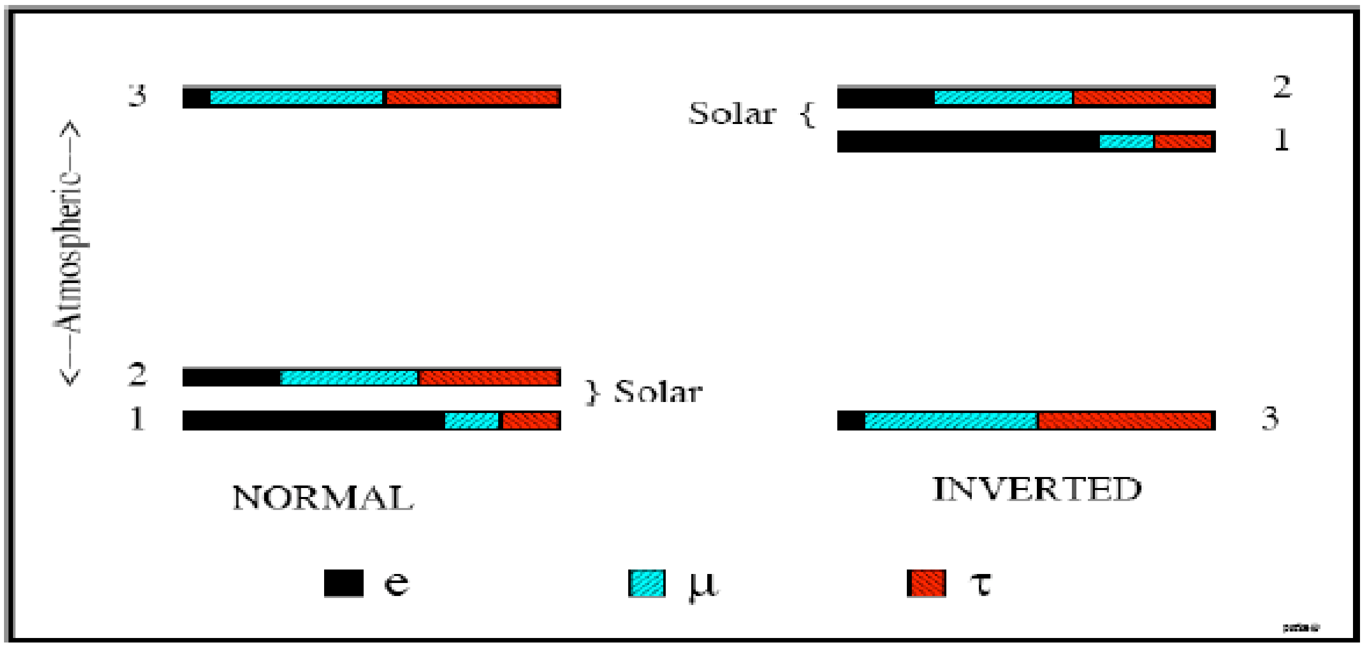
Outline

- Introduction
  - The Questions to Answer
  - The Equations
  - The Experimental Approach
- The Off-Axis Technique
  - The Basic Concept
  - The Experiments we can do
    - The Measurements we can make
    - The Physics we can extract
  - NuMI Off-Axis
    - Application in NOvA
    - Application for a NOvA2
- On-going Work - input to the LBL study
- Conclusions

The Questions

(in order of increasing difficulty)

- What is $\sin^2\theta_{13}$?
- What is the order of the neutrino mass hierarchy?
- Is CP violated in the neutrino sector?
  - i.e. is $\delta \neq 0,\pi$?

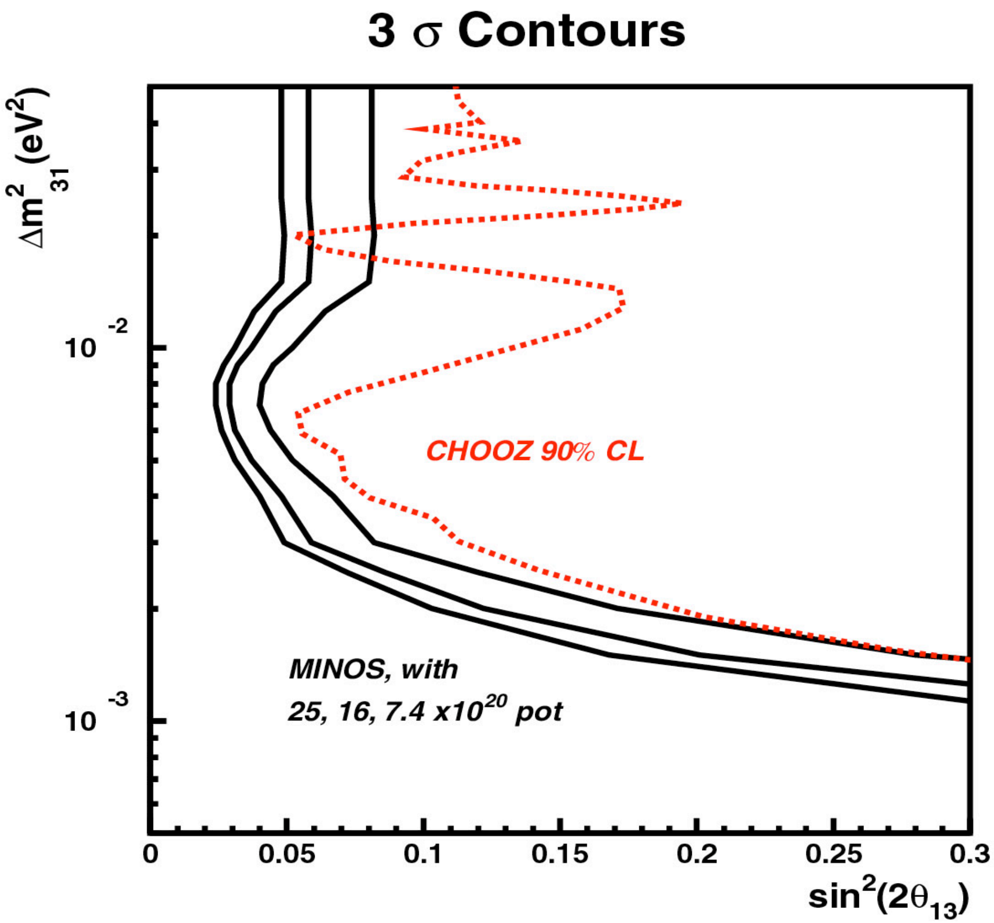


The Answers : a staged approached

- Step 1 : Current Program
  - operations 2005 - 2009-10
  - NuMI to MINOS
    - L = 735 km on-axis
    - LE beam
    - 12e20 POT
- Step 2 : Proposed Program
  - 2011 - 2016
  - NuMI to NOvA
- Step 3 : Current Discussion
  - A decade from now
  - Where we start, depends on outcome

  of Steps 1, 2 and other worldwide efforts

MINOS $\nu_\mu \rightarrow \nu_e$



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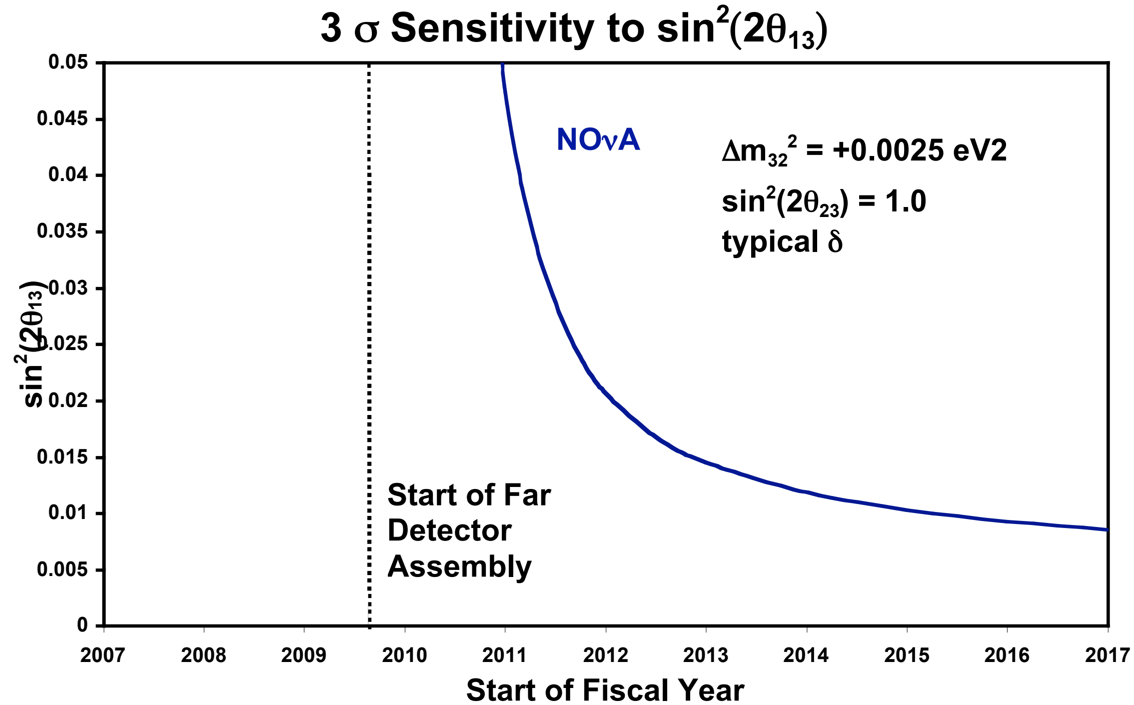
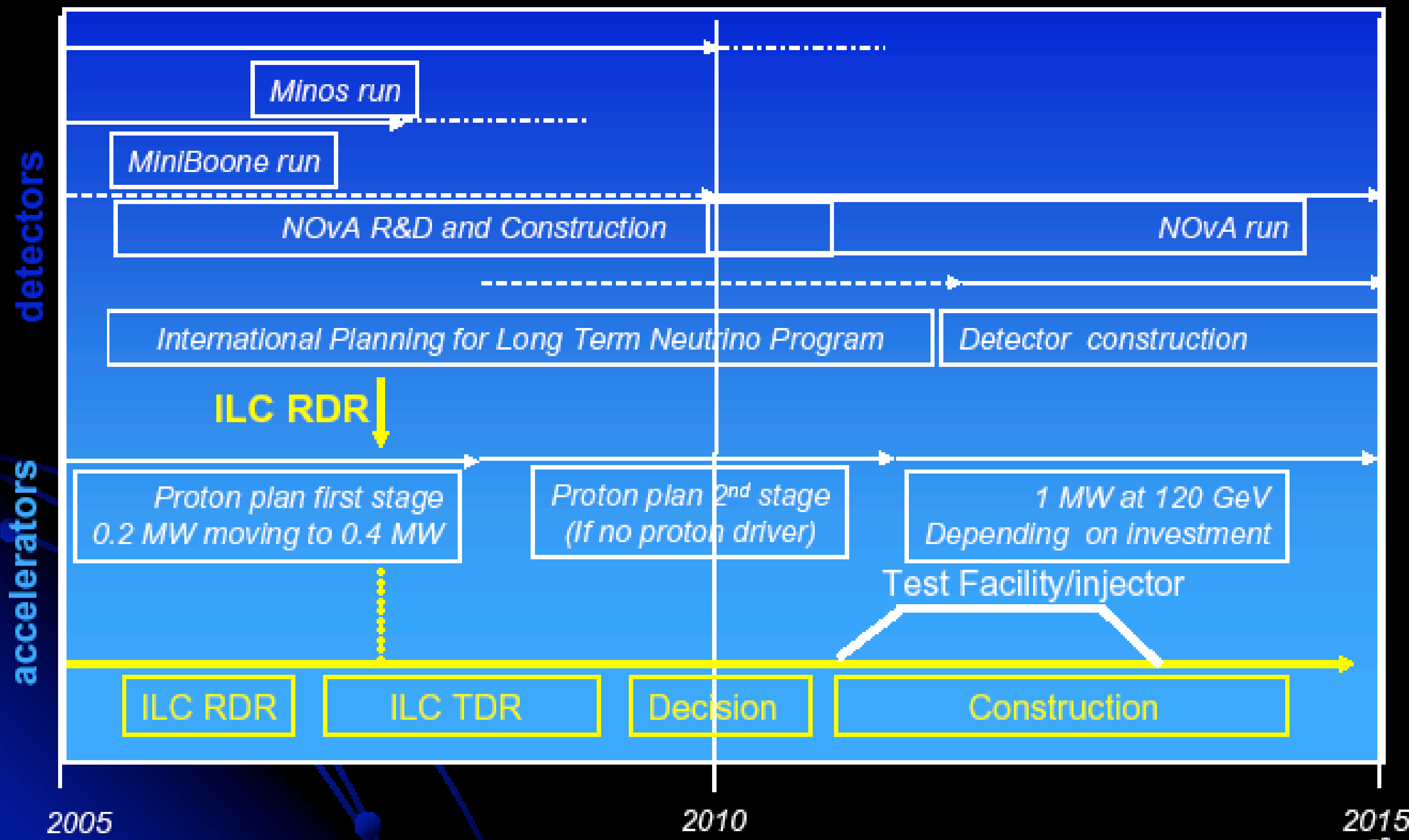
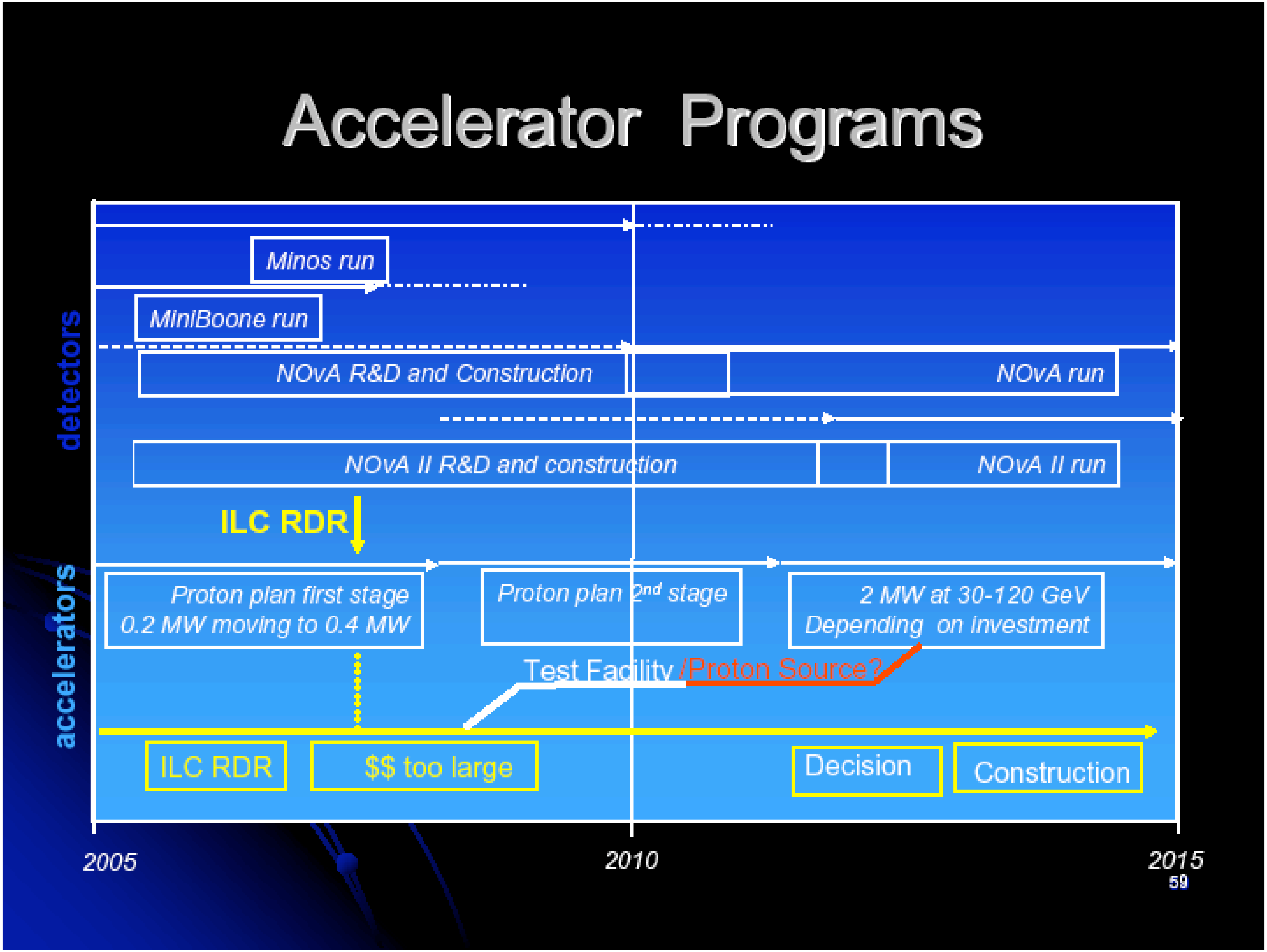
NOvA $\nu_\mu \rightarrow \nu_e$



Accelerator Programs





Accelerator Programs
detectors
accelerators
Minos run
MiniBoone run
NOvA R&D and Construction
NOvA run
NOvA II R&D and construction
NOvA II run
ILC RDR
Proton plan first stage
0.2 MW moving to 0.4 MW
Proton plan 2nd stage
2 MW at 30-120 GeV
Depending on investment
Test Facility /Proton Source?
ILC RDR
$$ too large
Decision
Construction
2005
2010
2015

Neutrino Mixing Matrix

solar

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

atmospheric

The Equations

- The simple version :

$$P(\nu_a \rightarrow \nu_b) = \sin^2 2\theta_{ab} \sin^2(1.27\Delta m_{ab}{}^2 L/E)$$

  - Works for the dominant oscillation mode
    - $\nu_\mu \rightarrow \nu_\tau$ Atmospheric
- Extend the simple version to the subdominant mode :

$$P_{vac}\left(\nu_\mu \rightarrow \nu_e\right) = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\Delta_{atm},$$

$$\Delta_{atm} \approx 1.27\left(\frac{\Delta m_{32}^2 L}{E}\right),$$

The Equations continue

- Matter effects ….

$$P_{mat}\left(\nu_\mu \to \nu_e\right) \approx \left(1 \pm 2\frac{E}{E_R}\right) P_{vac}\left(\nu_\mu \to \nu_e\right)$$

$$E_R = \frac{\Delta m_{32}^2}{2\sqrt{2}G_F N_e} = 12\ \text{GeV}\left(\frac{\Delta m_{32}^2}{2.5\times 10^{-3}\ \text{eV}^2}\right)\left(\frac{1.4\ \text{g cm}^{-3}}{\text{Y}_e\rho}\right)$$

- CP phase….

$$\Delta \text{P}_\delta(\nu_\mu \to \nu_e) \approx J_r \sin \Delta_{sol} \sin \Delta_{atm}(\cos\delta \cos\Delta_{atm} \mp \sin\delta \sin\Delta_{atm}),$$

$$J_r = \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \cos\theta_{13},$$

The Experimental Approach

- Depends on the "initial conditions"…
  - Existing accelerator ?
    - Proton/neutrino energies
  - Existing beamline ?
    - Beam direction
  - Desireable site ?
    - Baseline
    - Underground?
    - On surface?
  - Existing Detector ?
    - Detection threshold/efficiency
    - Baseline

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Fermilab :
50 - 120 GeV protons
NuMI beam :
neutrinos aimed down
At 57 mrad to Soudan,
Minnesota 700 km <L< 900km

The Experimental Approach

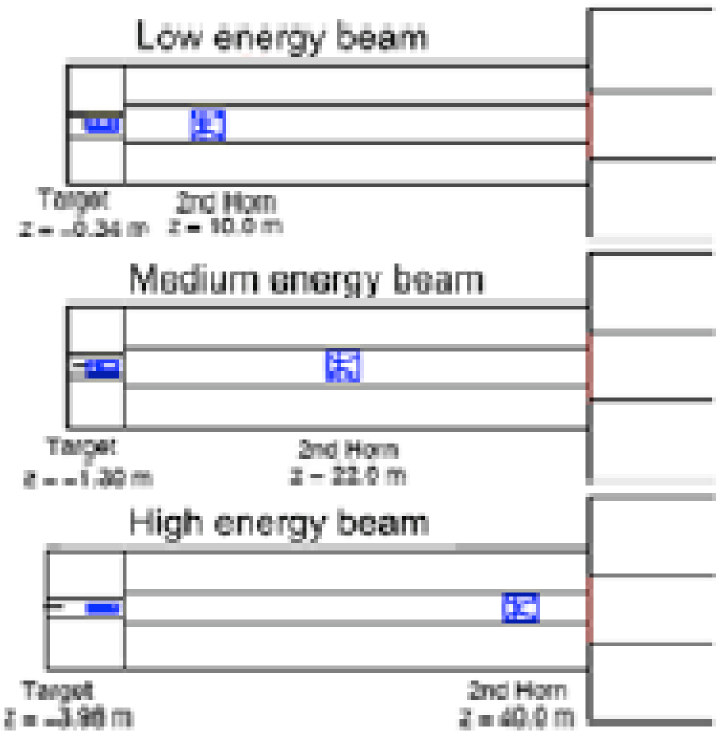
- Existing Conditions or Optimized Parameters (i.e.)
  - baseline (L)
  - initial beam composition ($\nu_\mu, \overline{\nu_\mu}, \nu_e$)
  - unoscillated energy spectrum (E)
  - detection efficiency

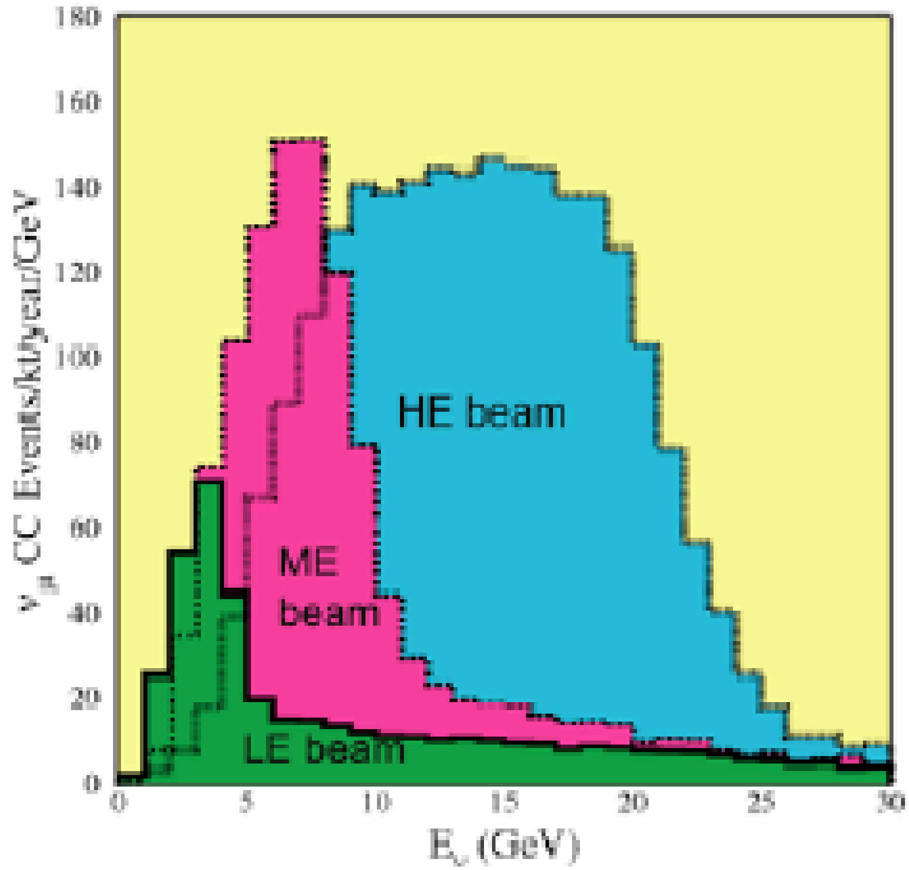
… will determine

  - # of events expected in the absence of oscillation

- Physics will determine
  - # of events (of each flavor)
    - *appearing* and *disappearing* due to **oscillation parameters**, **CP phase** and matter effects
    - ν and anti-ν rates differ due to **mass hierarchy** and **CP phase**
- Multiple measurements are needed to disentangle effects

Variable Energy NuMI Beam



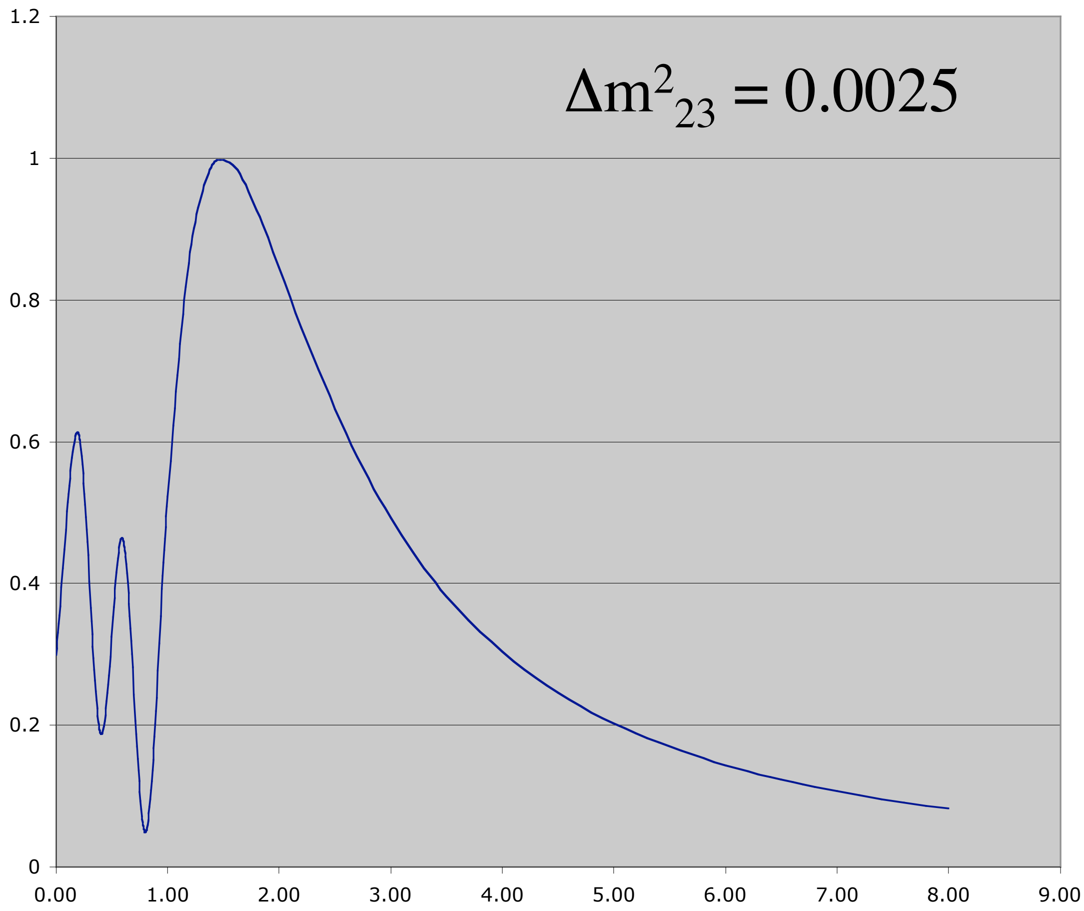


Presentation to NuSAG
May 20, 2006

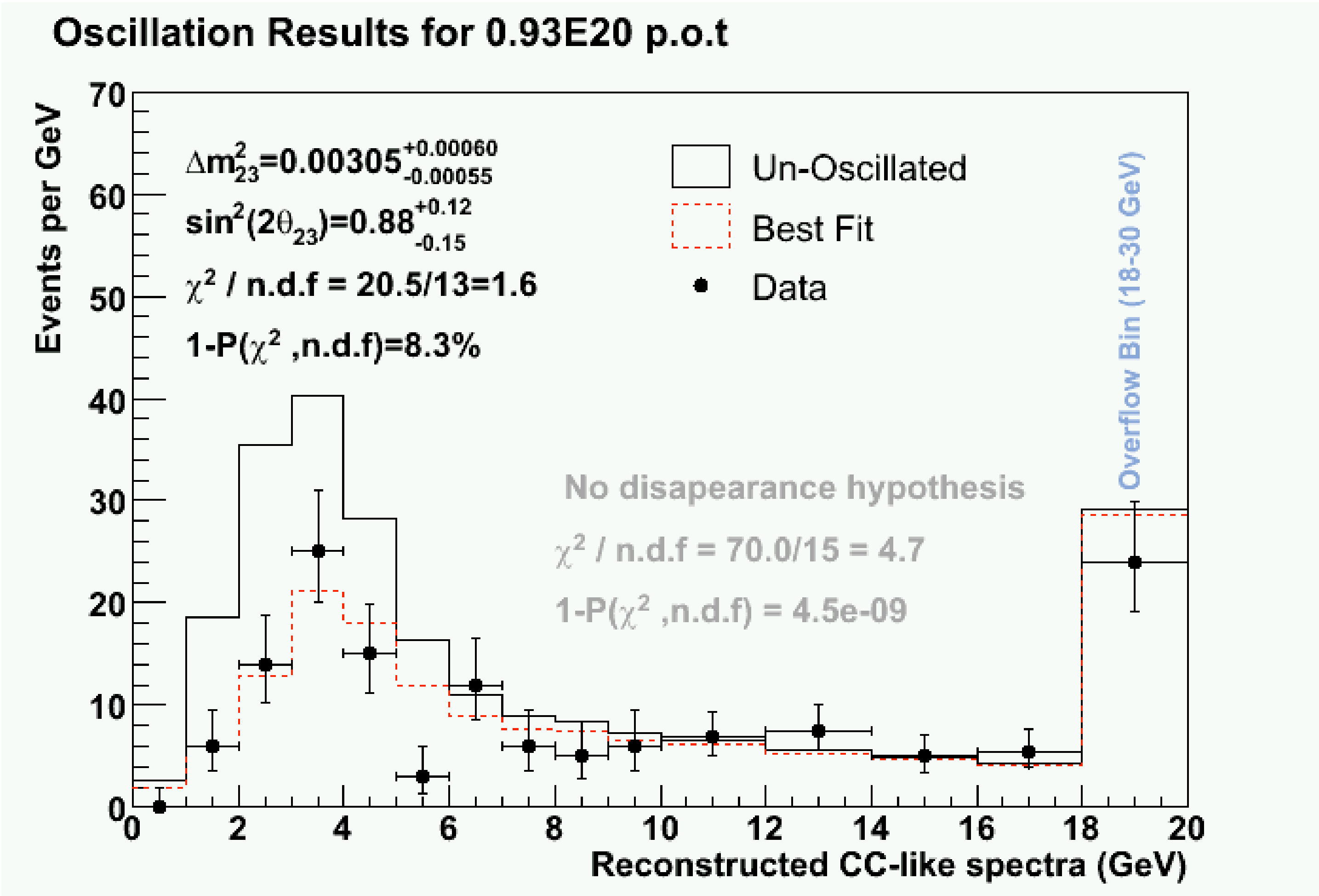
Oscillations at L = 735 km

L determined by an existing Laboratory

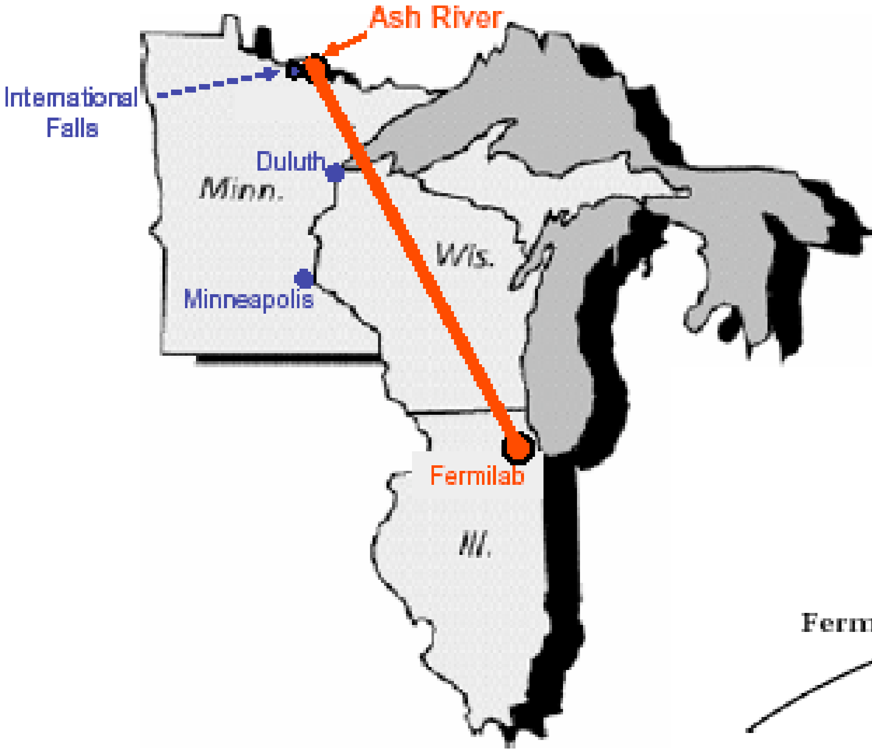
- $\nu_\mu \rightarrow \nu_\tau$

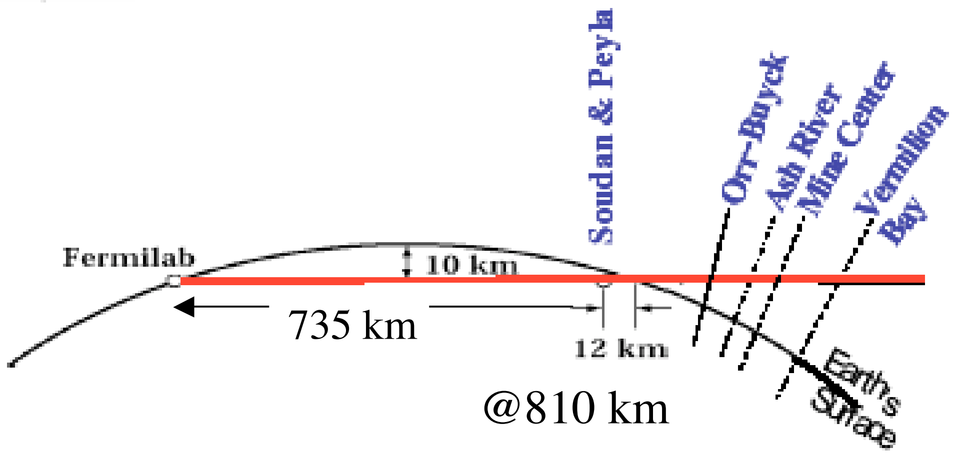


Dominant $\nu_\mu \rightarrow \nu_\mu$ disappearance
a.k.a. MINOS



The Experimental Approach : "NuMI North"



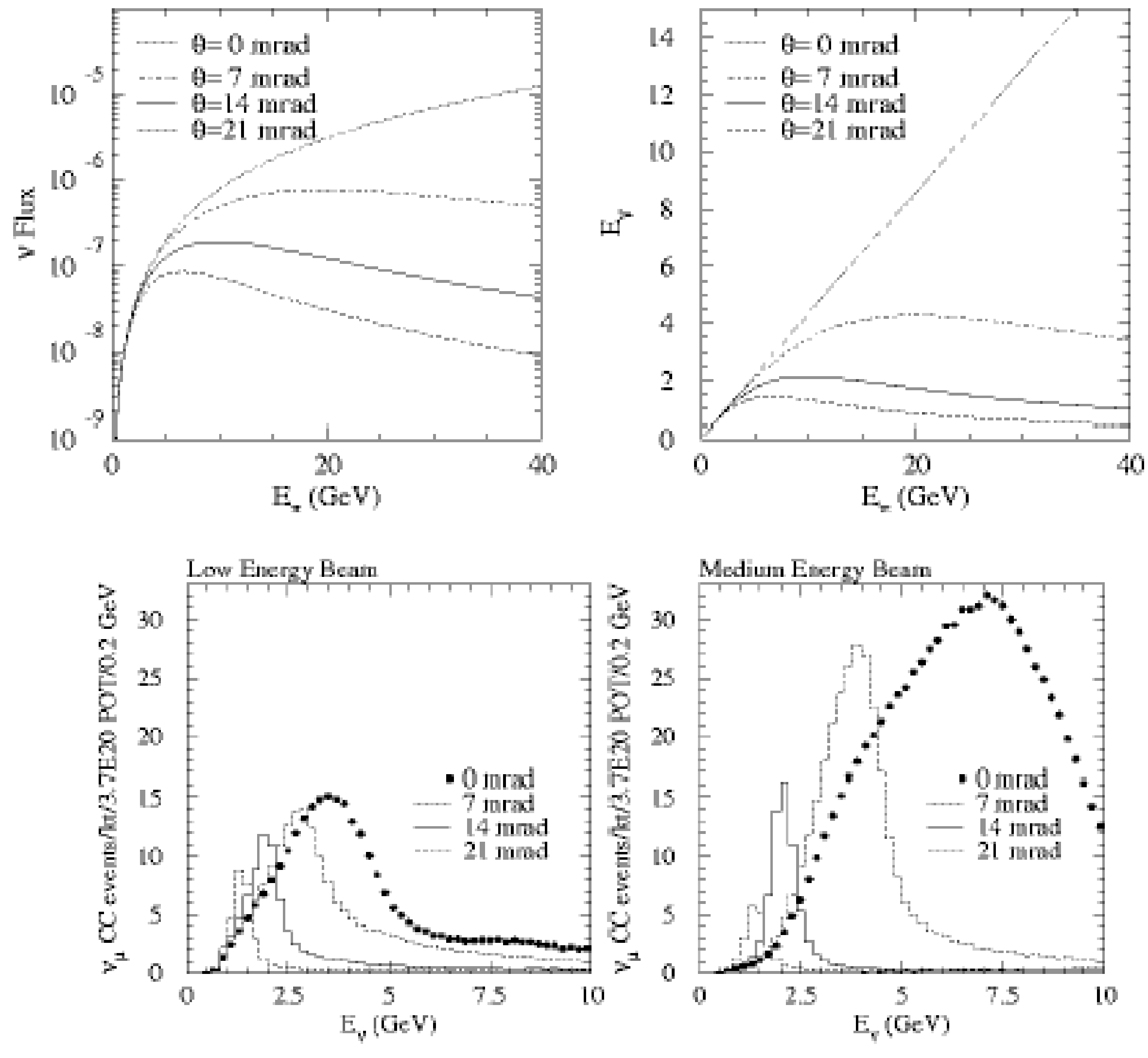


@810 km

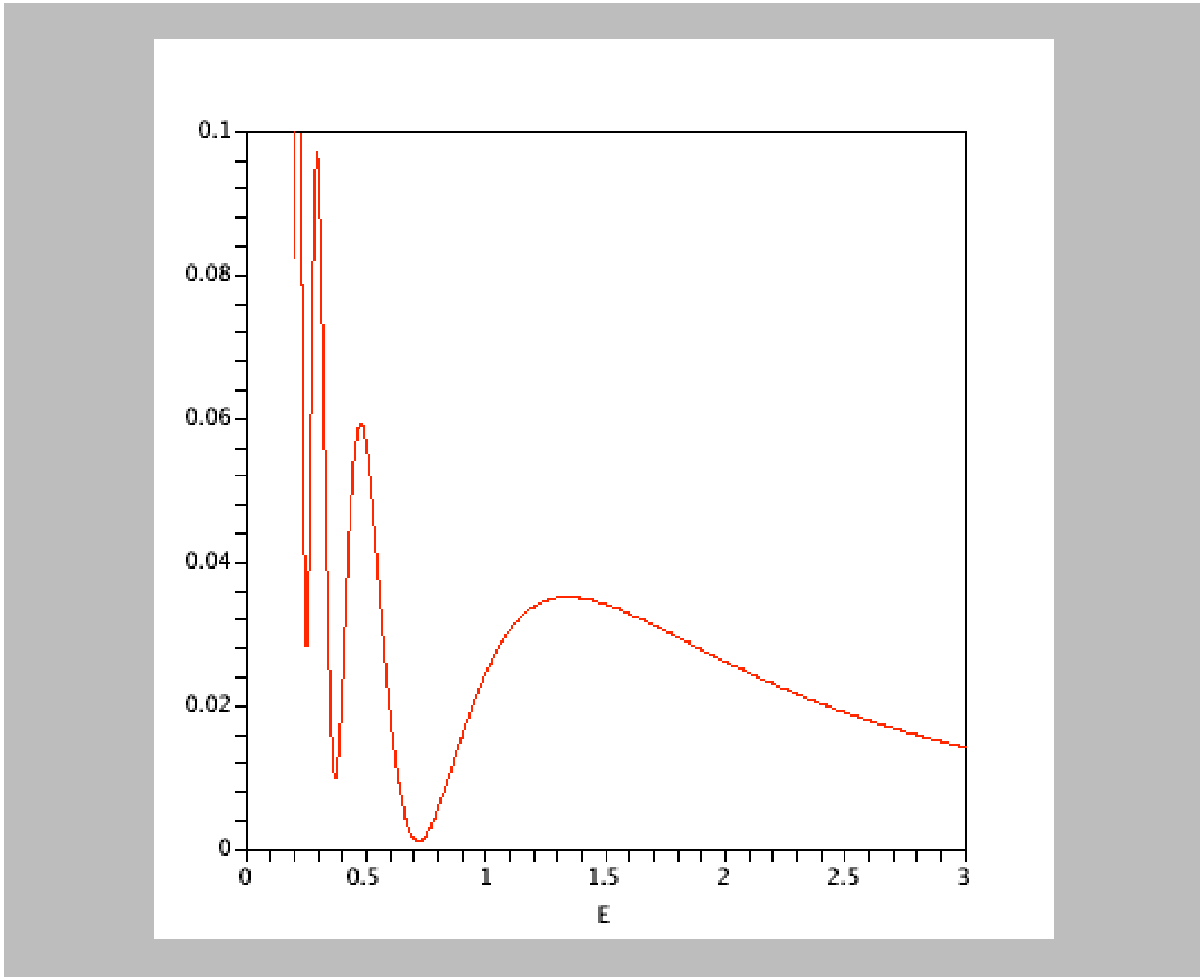
12 km off-axis

~ 14 mrad

The Off-axis concept



Sub-dominant $\nu_\mu \rightarrow \nu_e$ appearance



Example :
L = 810 km
$\Delta m^2_{23} = 0.0025$
$\theta_{23} = 0.642$
$\theta_{13} = 0.15$

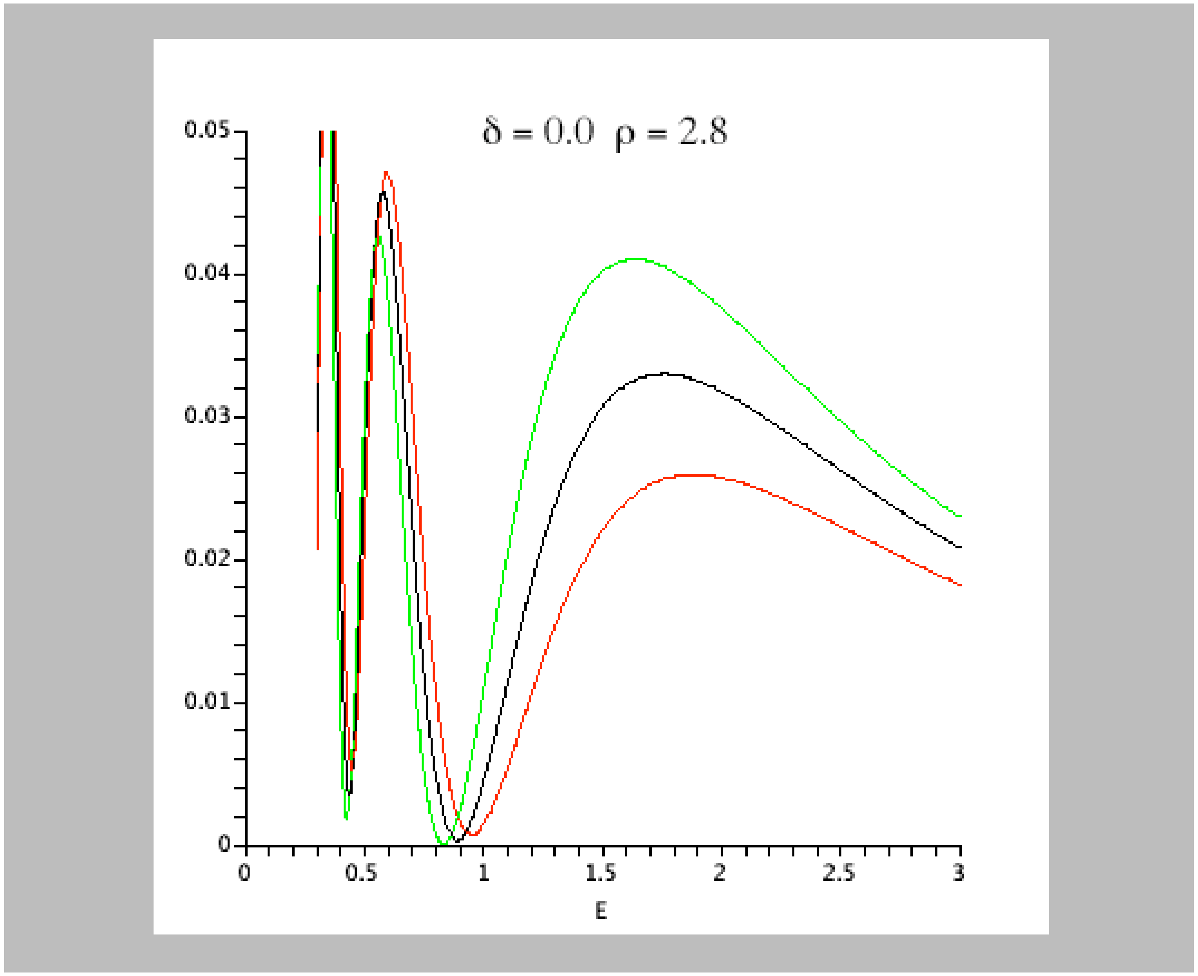
Event Rates at the 1st Maximum

$$P_{vac}\left(\nu_\mu \to \nu_e\right) = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\Delta_{atm},$$

$$\Delta_{atm} \approx 1.27\left(\frac{\Delta m^2_{32} L}{E}\right),$$

- Determining θ_{13}
  - Input physics parameters :
    - $\sin^2\theta_{23}$
    - $\Delta m^2_{atm} \sim \Delta m^2_{32}$
    - Neutrino cross sections
  - Input experimental parameters
    - Protons per year
    - Neutrino spectrum
      - Detector Location (L, Δx)
    - Detector fiducial mass, efficiency

Oscillations affected by matter



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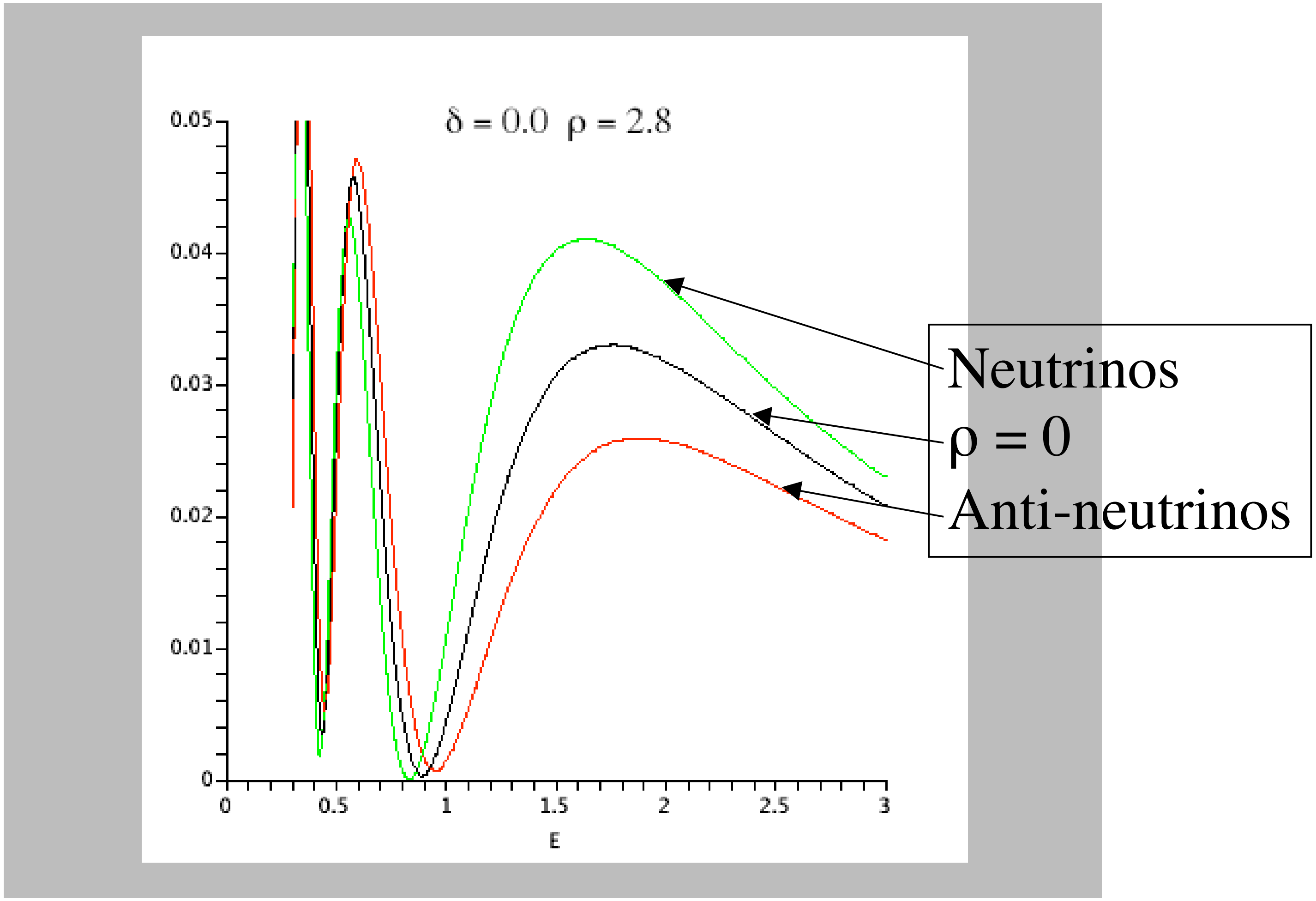
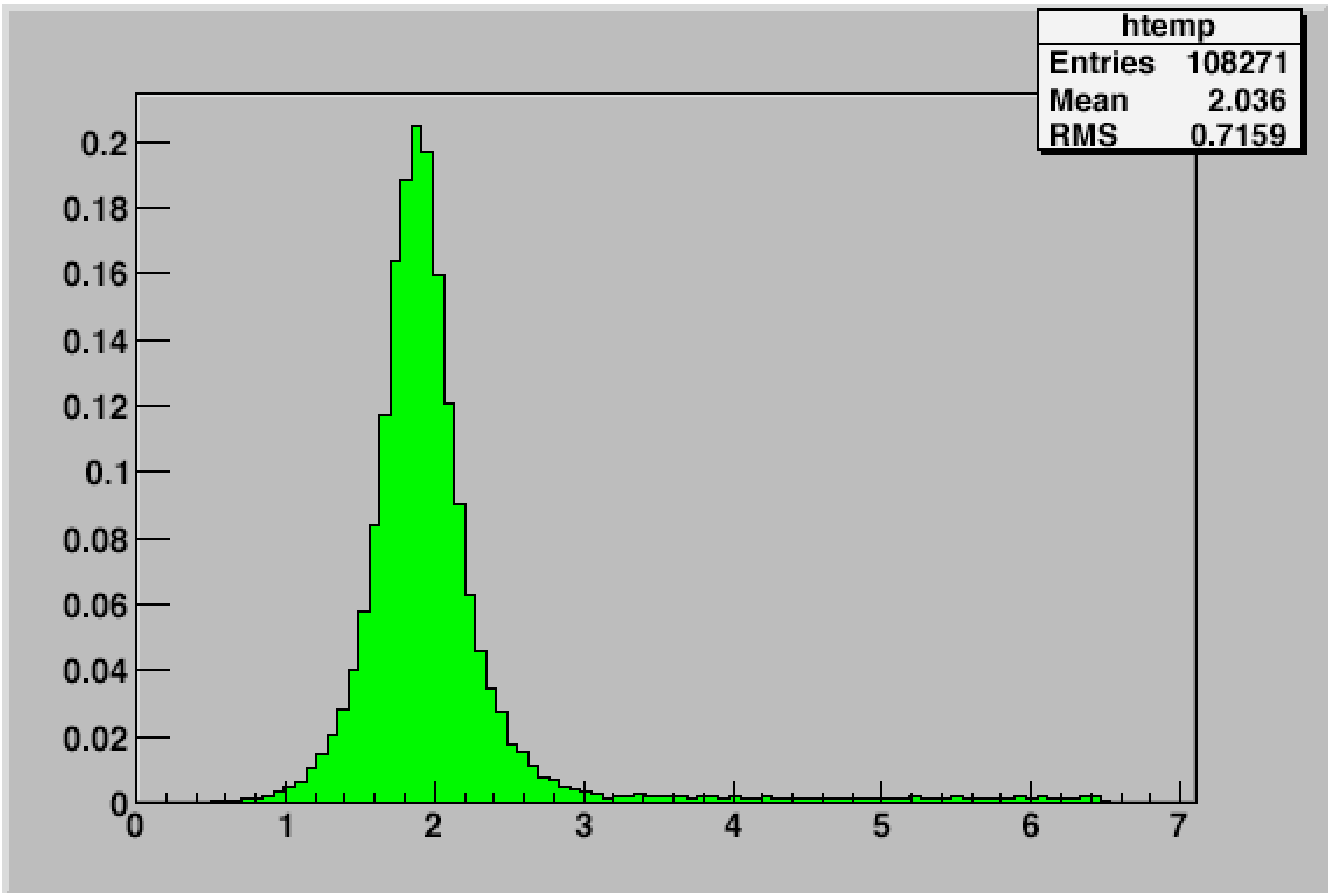
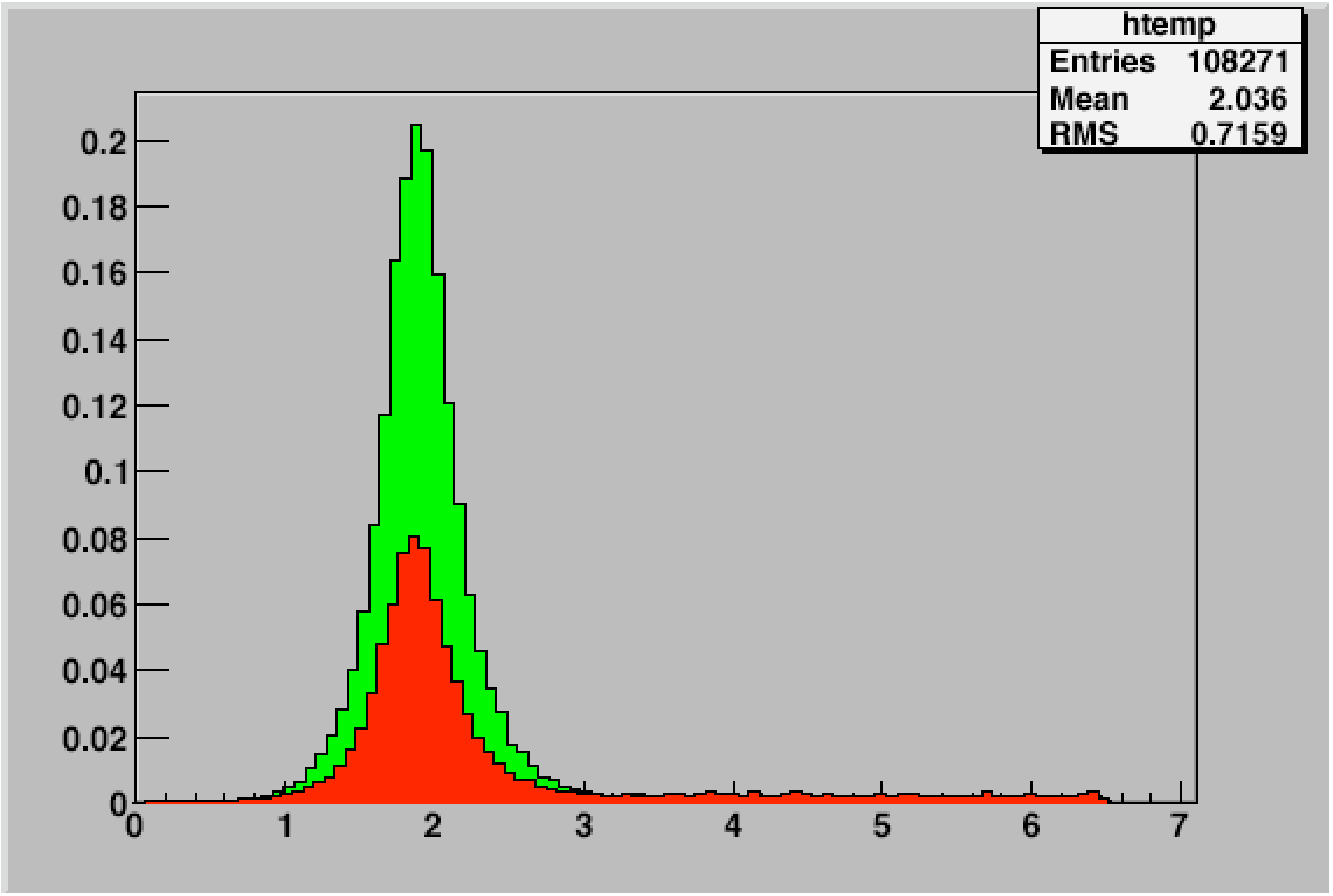


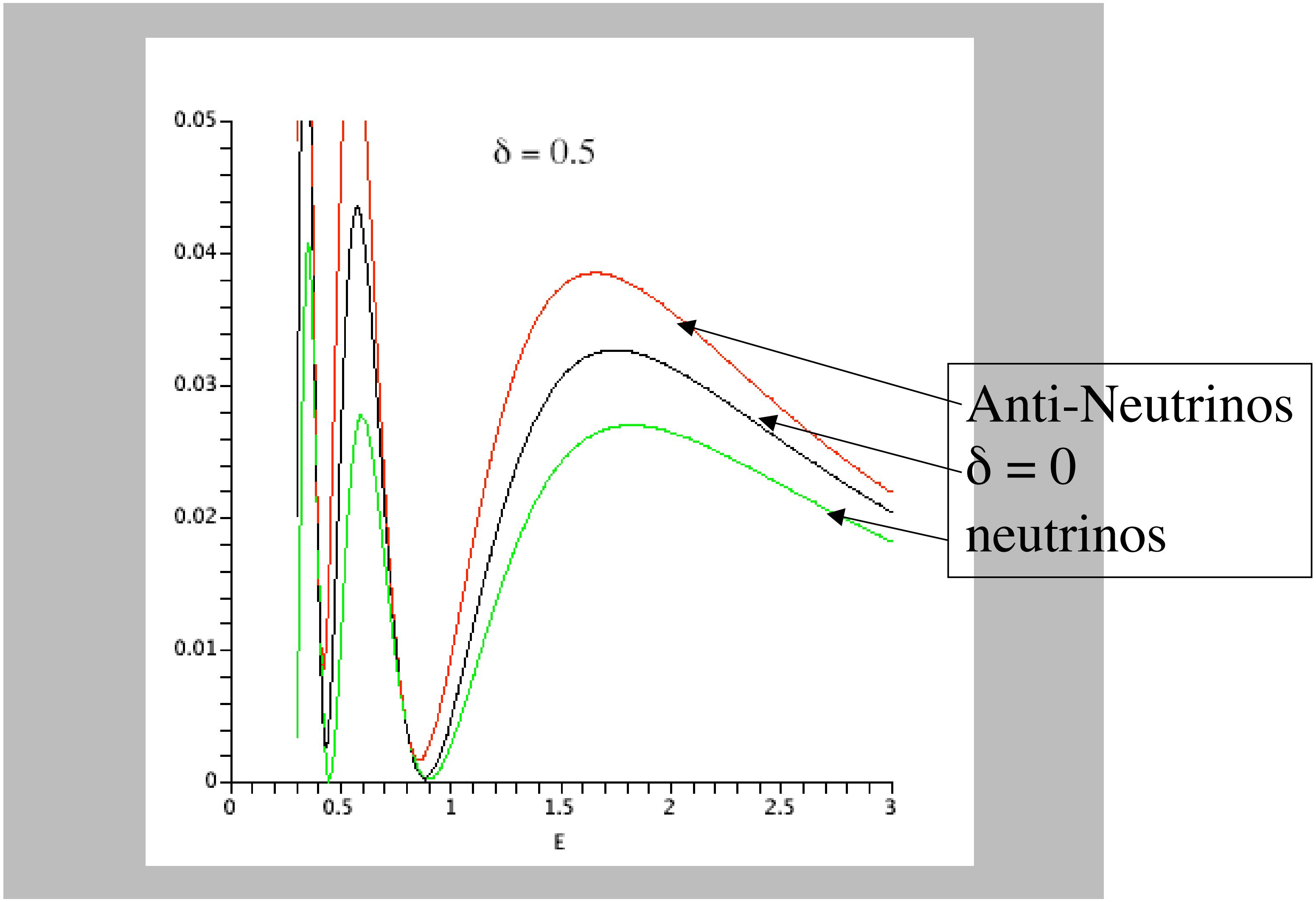
Create a beam : 810 km, 14 mr off xis



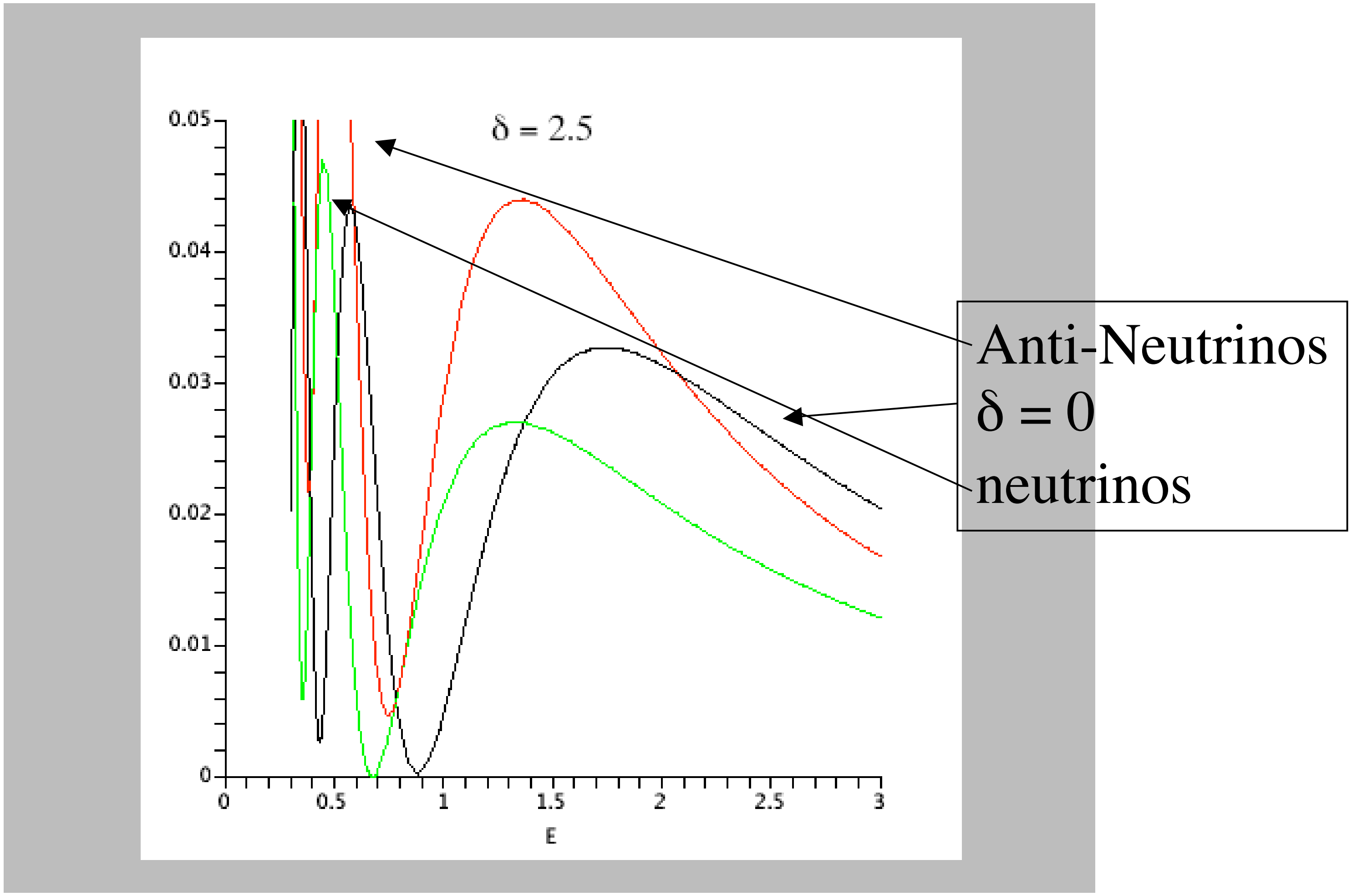
Change horn currents (anti-neutrinos)



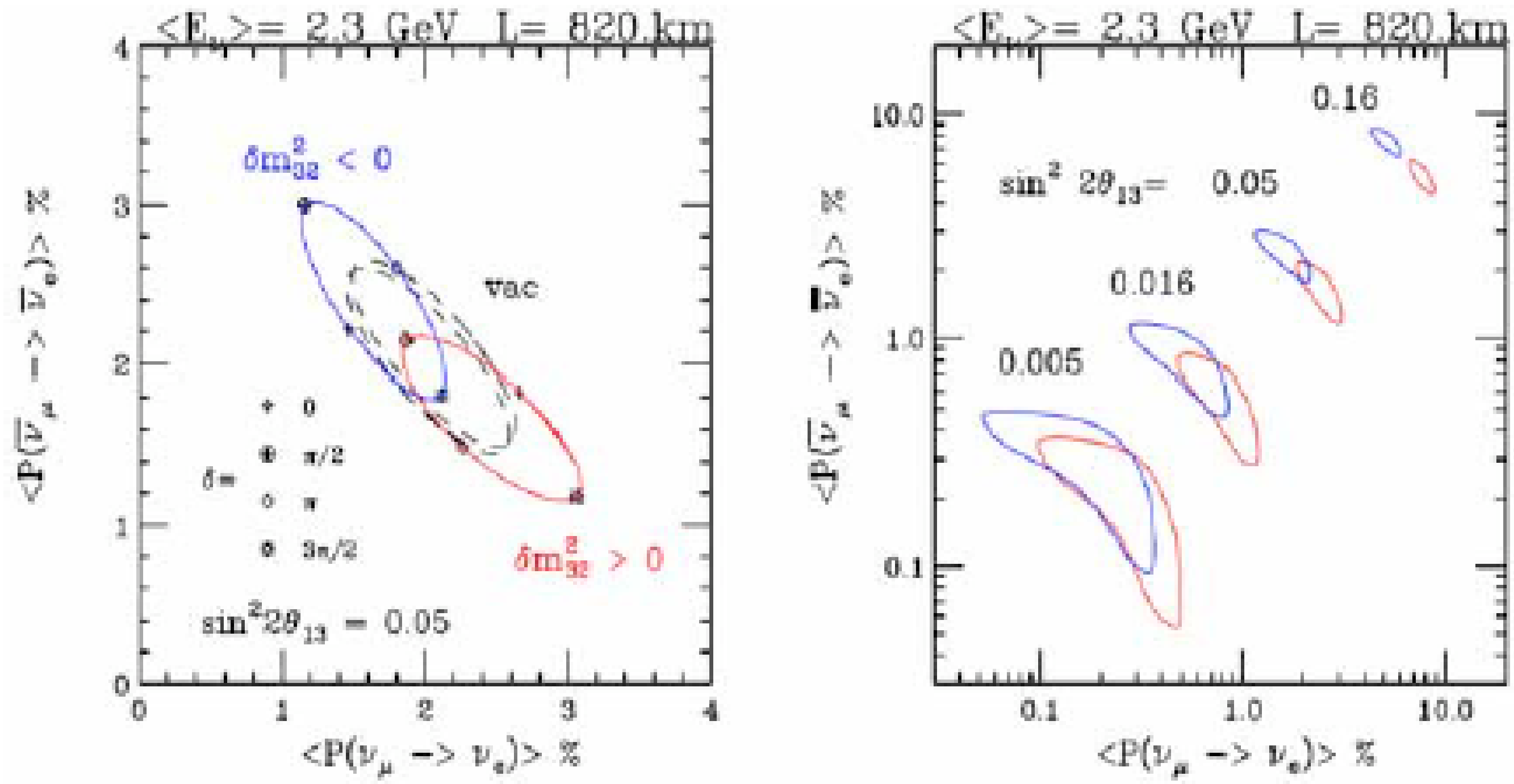
But life isn't simple…



And we have no idea what δ is…

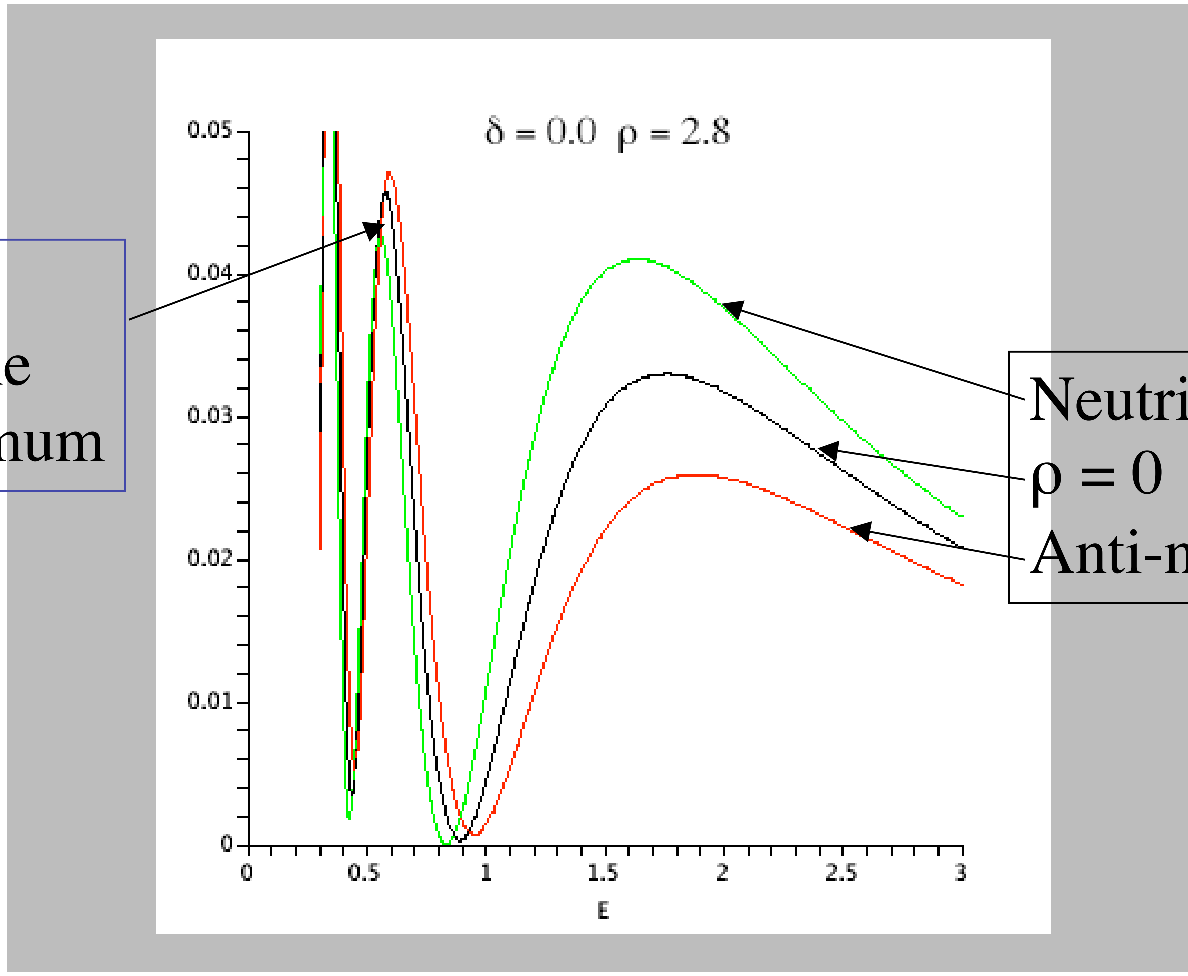


Measurements ?



Oscillations affected by matter

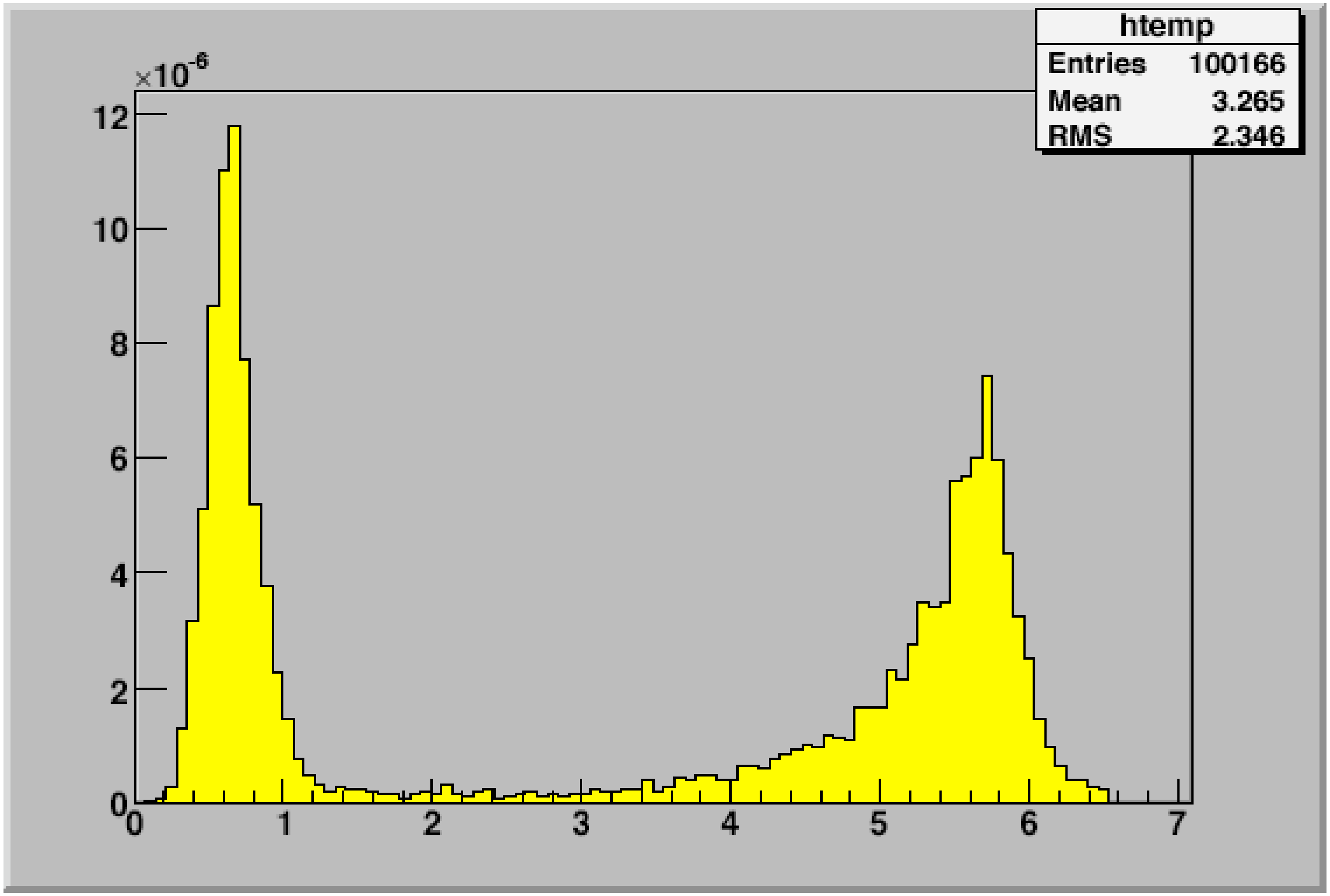
But not so much at the 2nd maximum



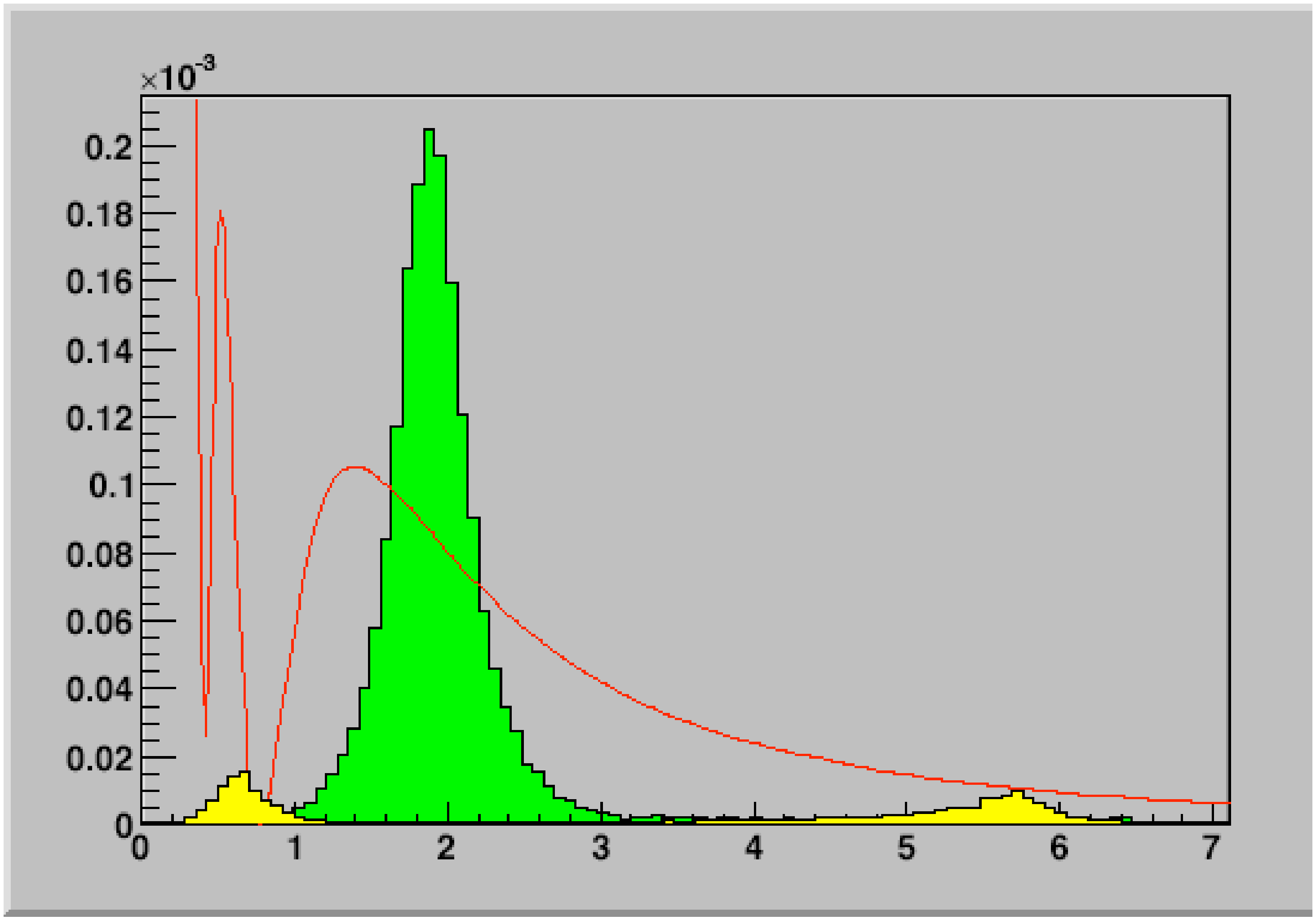
Neutrinos
ρ = 0
Anti-neutrinos

Normal hierarchy

NuMI Off-axis - 40 mrad (32 km)



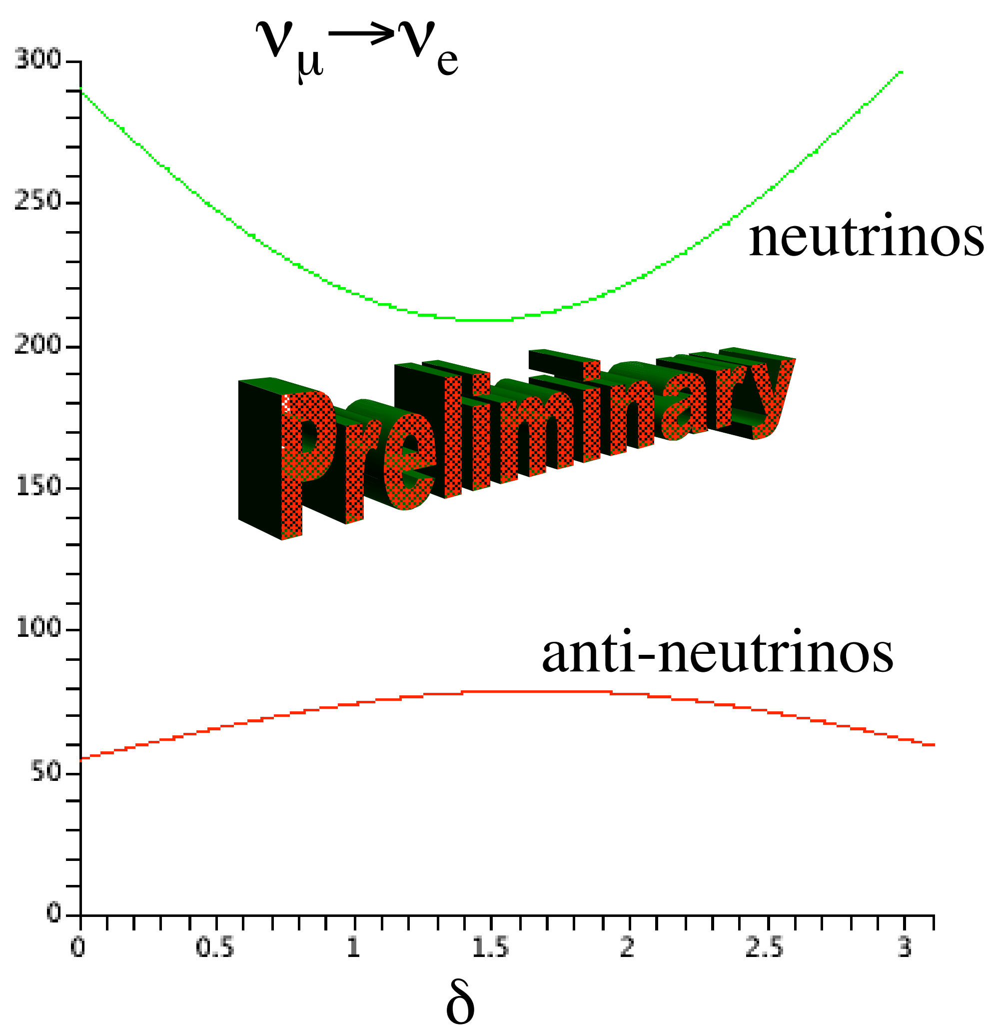
$\nu_\mu \rightarrow \nu_e$ appearance



Example : L = 810 km
$\Delta m^2_{23} = 0.0025$

Event Rates

$L = 810$ km
12 km OA
20 kt fiducial
20e20 pot (~3yrs)
(for each mode)
$\Delta m^2_{23} = 0.003$
$\theta_{13} = 0.15$
Normal hierarchy



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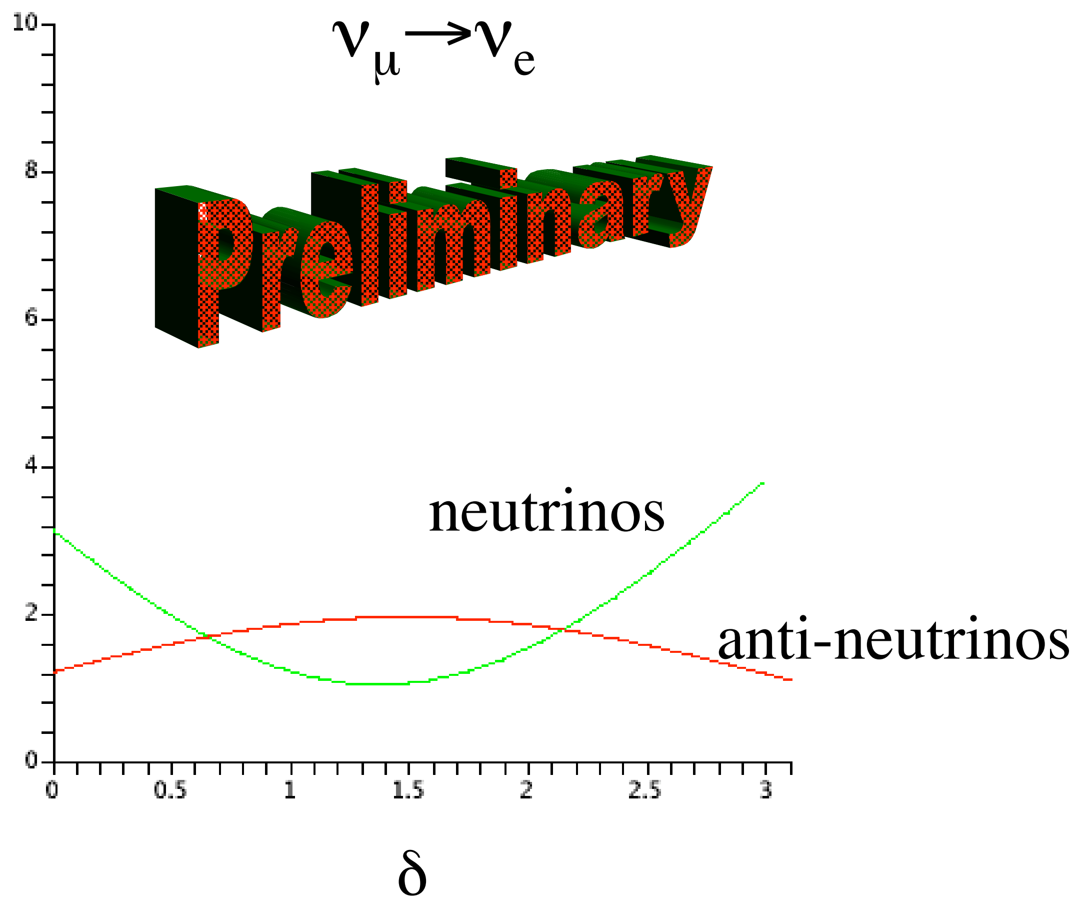


Backgrounds

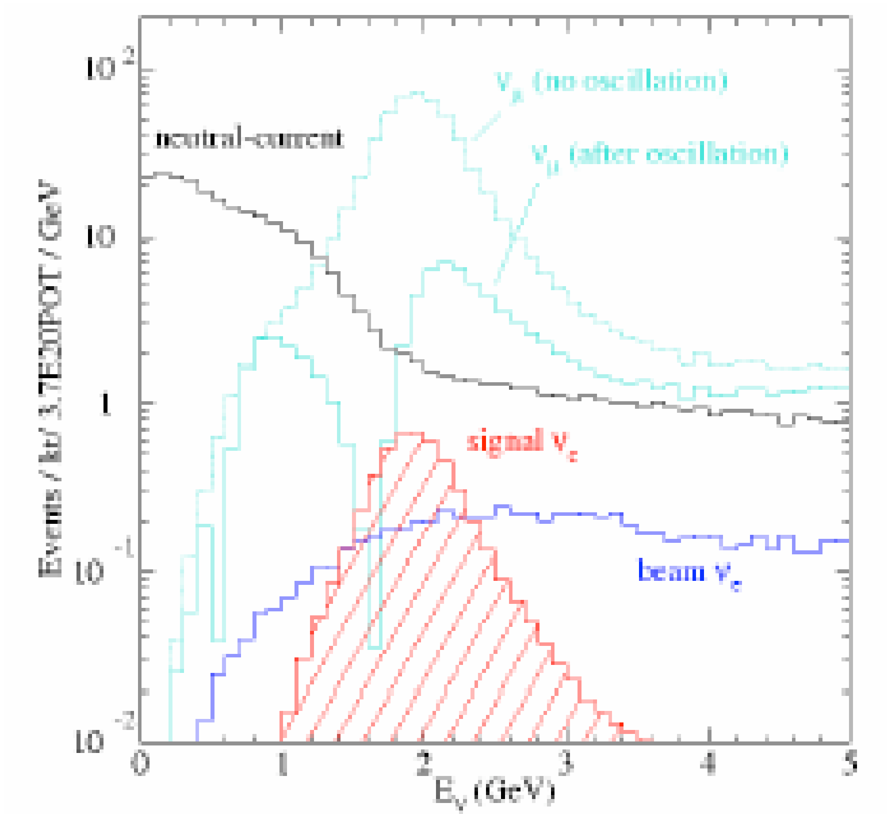
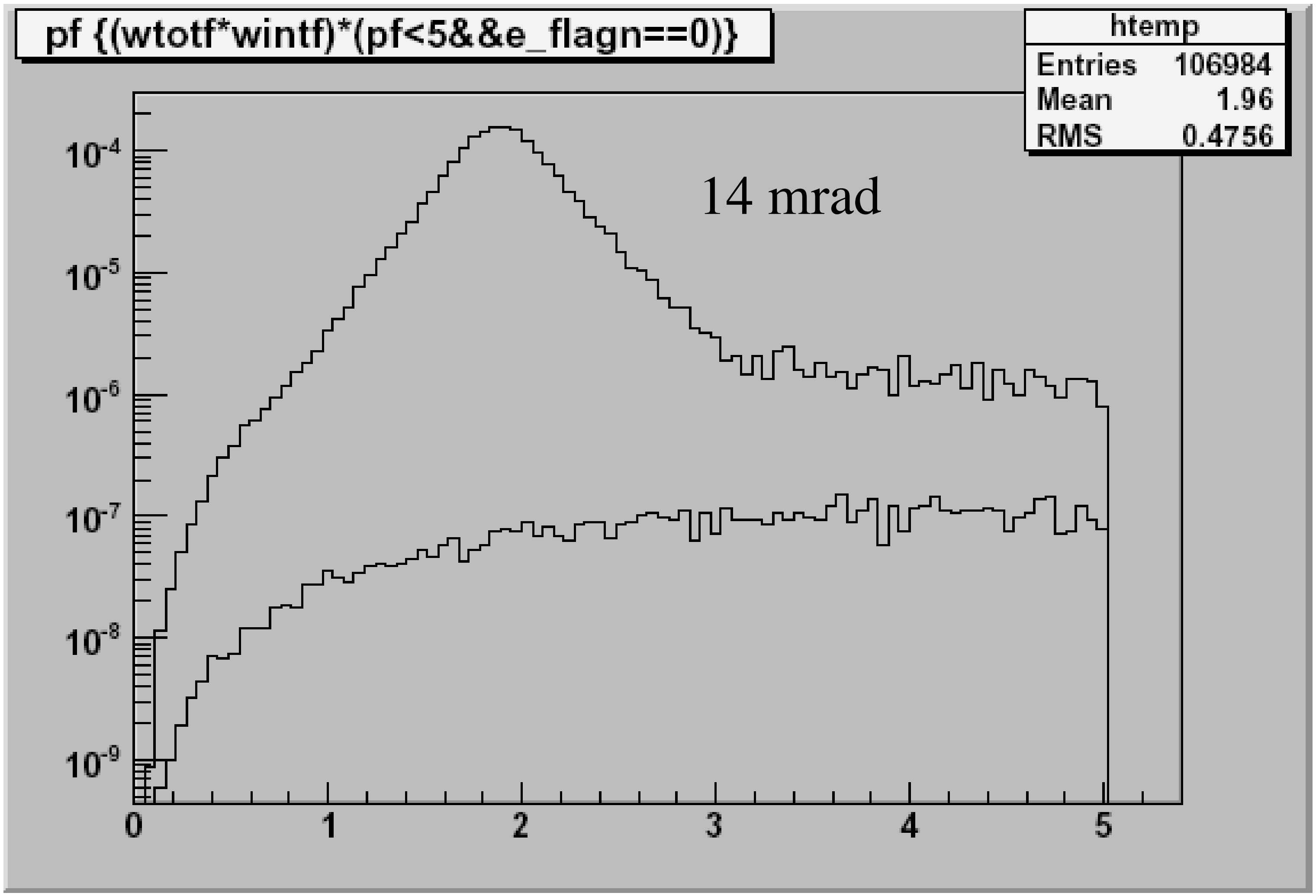


Fig. 2.8: Simulated energy distributions for the ν_e oscillation signal, intrinsic beam ν_e events, neutral-current events and ν_μ charged-current events with and without oscillations. The simulation used $\Delta m^2_{32} = 2.5 \times 10^{-3}$ eV^2, $\sin^2(2\theta_{23}) = 1.0$, and $\sin^2(2\theta_{13}) = 0.04$. An off-axis distance of 12 km at 810 km was assumed.

Backgrounds (cont)



Conclusions (1)

- An Off-axis neutrino beam is a powerful tool for measuring oscillation parameters and the neutrino mass heirarchy
- The success of experiments using this technique depend heavily on the ability of the proton source to deliver lots of protons
- In the best of worlds $\sin^2 2\theta_{13} \sim 0.1$ the experiments are difficult and take a long time to proceed through the list of questions
- If nature is cruel, $\sin^2 2\theta_{13} \sim 0.01$, we will most likely need multi-megawatt proton beams aimed at megaton detectors.

Conclusions (2)

- FMI Operations (January 2005 -February 2006) have delivered 1.4e20 protons to the NuMI target (1.3e20 in the Low energy configuration)
- MINOS experiment is counting on getting ~3e20 protons/year for 2007 - 2009
- The NOvA experiment is planning on ~> 6.5e20/year (700 kw) starting in 2011 (see Alberto's talk)

Conclusions (3)

- An off-axis experiment at the 2nd oscillation maximum will require :
  - increased protons (> 1 MW) ?
  - more mass (50 - 100 kton) ?
  - higher efficiency (~80%) ?
  - longer running time (10 yrs) ?
- Measuring the neutrino sector CP phase
  - priceless

On-going/Upcoming Work

- Complete event rate analysis for 1st and 2nd maximum at L~810 (12 and 32 km off-axis)
- Study L~250km sensitivity
- Study sensitivity at longer baselines (1500, 2500 km)
- Validate background estimates for beam
- Compare to wide band beam scenarios

A final comment

- In addition to the experiments being difficult from the signal to background point of view, collecting a handful events/year for many years will require some new thinking about how to manage and retain experimental collaborations
- Expanding the capability of the detectors to have more physics reach may be a necessary investment